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RESEARCH MEMORANDUM

AN INVESTIGATION OF THE DOWNWASH BEHIND A HIGH-ASPECT-RATIO WING WITH VARIOUS AMOUNTS OF SWEEP IN THE LANGLEY 8-FOOT HIGH-SPEED TUNNEL

By

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Downwash angles have been measured at points at two vertical positions at the probable tail location behind a high-aspect-ratio wing with an NACA 65-210 section with no sweep and 30° and 45° of sweepback and sweepforward in conjunction with a fuselage at Mach numbers up to 0.96 in the Langley 8-foot high-speed tunnel. The results of these measurements show the variations of downwash with normal-force coefficient and Mach number, but not the absolute values of downwash for any condition. The results indicate that the downwash angle for a given normal-force coefficient behind the wing without sweep increases rapidly when the Mach number is increased beyond the force break and decreases sharply at a Mach number approximately 0.1 greater than that at which it increases. The changes in the downwash angle for given normal-force coefficient with Mach number behind the wing with 30° of sweepback are qualitatively similar to those that occur behind the wing without sweep, but they are delayed by sweep by approximately the same Mach number increment as is the force break. The downwash angle for a given normal-force coefficient behind the wing with 45° of sweepback changes very slightly when the Mach number is increased up to the highest test value, as do the normal-force and profile-drag coefficients for a given angle of attack. The variations of the downwash angles for given normal-force coefficients with Mach number for the wing with 30° of sweepforward are very erratic, varying considerably with normal-force coefficient and survey position. The rates of variation of downwash angle with normal-force coefficient for the wing with 45° of sweepforward are very large at moderate normal-force coefficients.

INTRODUCTION

Very little detailed information concerning the effect of compressibility on the flow around swept and unswept wings at high subsonic speeds is available. In order to obtain additional information on compressibility effects, extensive pressure measurements have been made

on and behind a high-aspect-ratio wing with NACA 65-210 sections and no sweep and modified to obtain 30° and 45° of sweepback and sweepforward. Tests were made for all sweep configurations of the wing in conjunction with a midwing fuselage. These measurements have been made at Mach numbers from 0.6 to 0.96 in the Langley 8-foot high-speed tunnel. The normal-force, pitching-moment, profile-drag, and aerodynamic-loading coefficients for the wing and fuselage obtained from these pressure measurements are presented in reference 1. Presented herein is an analysis of the effects of compressibility on the downwash as determined from yaw-head measurements made at two vertical positions in the region of the probable tail locations of conventional airplanes.

APPARATUS

The wing-fuselage combination used for this investigation is described in reference 1. The model was supported in the tunnel by means of the vertical steel plate as described in reference 2, and sweep was obtained by rotating the wing with respect to the plate. The plan form of the semispan combination with 30° of sweepback is shown in figure 1. The general dimensions of the various swept configurations are given in table I.

The downwash angles at the two vertical positions behind the various configurations were measured by two small yaw heads with the dimensions shown in figure 1. Total pressures at the positions of the yaw heads were measured by means of total-pressure tubes placed at the centers of the yaw heads as shown in the same figure. The yaw heads were attached to the fuselage by means of a curved strut as shown in figure 1. The positions of the yaw heads with reference to the various configurations are given in table I. The yaw heads were calibrated at the test Mach numbers by rotating them through various angles with respect to the support.

ERRORS AND CORRECTIONS

The differences between the readings of the two yaw tubes of a given yaw head for the calibration and test runs have been converted to non-dimensional coefficient form by dividing the differences by the local-dynamic-pressure values determined, assuming the local-static-pressure values to be equal to the stream static pressure. The effect of such an assumption on the downwash angles is assumed to be negligible. The yaw-head calibrations obtained for a given stream Mach number have been used to determine the downwash angles at that stream Mach number regardless of the values of local Mach number. The effect of variations in Mach number on the calibrations is small, however, and the errors introduced into the results by the use of such a method are negligible for most conditions.

An analysis of possible sources of error indicates that, for the conditions at which there is only a small variation of the local Mach number from the stream Mach number, the maximum error in the change in the downwash angle produced by either a change in normal-force coefficient or Mach number is less than 0.1°. For the few conditions where the yaw head became enveloped by the wake and the conditions at the yaw heads differed considerably from those present during the calibration runs, the downwash angles presented may be considerably in error. The wake enveloped the yaw heads principally at the higher normal-force coefficients and Mach numbers for the wings with 30° and 45° of sweepforward.

The settings of the yaw heads for given runs may have inadvertently been in error by some angle less than 1.0°. Therefore, although the changes in the downwash angle produced by variations of the normal-force coefficient or Mach number are usually in error by less than 0.1°, the absolute magnitude of the downwash angles presented may be in error by as much as 1.0°.

The cross flow at the survey positions was probably very small, and the error due to such cross flow is therefore probably negligible for all test conditions.

The Mach numbers have not been corrected for tunnel-wall interference. Estimations of the order of magnitude of this interference, using the expressions presented in reference 2, indicate that the corrections to be applied to dynamic pressure and Mach numbers for all conditions except that of no sweep at a Mach number of 0.925 are less, and in most cases much less, than 1 percent. The corrections to be applied to the Mach numbers for no sweep at a Mach number of 0.925, the maximum test value for this configuration, may be as large as 3 percent. The downwash angles have been corrected for tunnel-wall interference, using the equations presented in reference 3 which are for an unswept wing. The downwash corrections applied at Mach numbers of 0.6 and 0.925 were approximately 6 and 8 percent of the measured values, respectively.

RESULTS

The downwash angles have been determined for the same Mach numbers and angles of attack as those at which the pressure measurements were made on the wing (table II). The variations of downwash angles with normal-force coefficient at the various Mach numbers and for the two yaw-head positions and the five sweep angles are presented in figure 2. The variations of the downwash angles with Mach number for normal-force coefficients of 0.2, 0.4, and 0.6 for the various sweeps are presented in figure 3. The normal-force coefficients used are those obtained for the complete wing-fuselage combination and are defined in reference 1. These coefficients are very nearly equal to the lift coefficients for identical conditions. Any discrepancy is less than that due to the probable maximum error in the measured angles. The variations of the normal-force coefficients for complete wing-fuselage combination with angle of attack are presented in figure 4. The symbols used on the figures are defined in table I.

When the Mach number was increased from 0.60 to 0.96, the Reynolds numbers for the unswept wing based on the mean chord varied from 1.05×10^6 to 1.25×10^6. The Reynolds numbers for the swept wings were greater than these values by the ratios of chords of the swept wings to the mean chord of the unswept wing (table I).

DISCUSSION

Unswept configuration.- For test angles of attack up to those at which the wing begins to stall (fig. 4(a)), the variations of downwash angle with normal-force coefficient are very nearly the same at most Mach numbers up to the highest test value, 0.925 (figs. 2(a) and 2(b)). The data obtained at a Mach number of 0.6 indicate that when wing stall occurs the downwash angle increases abruptly. This increase may be attributed to the presence of the strong wake that passes below the point of measurement; as pointed out in reference 4, the turbulent mixing and diffusion of the wake causes a gradual reduction of its displacement thickness, with a consequent inflow of the surrounding air toward the center of the wake, corresponding to an increase of downwash above the wake and a decrease of downwash below the wake. The wing stall and the increase in downwash associated with it may probably be affected by increasing the Reynolds number.

At a Mach number of 0.89 and very low and negative normal-force coefficients, the variation of downwash with normal-force coefficient is greater than the variations for the other conditions.

As the Mach number is increased to the value at which the flow over the surface of the wing separates due to the onset of shock, that is, the force-break Mach number, as indicated in figure 10 of reference 1 and by the dashes in figure 3, the downwash for a given normal-force coefficient decreases gradually, due to the contraction of the potential-flow field around the wing in the stream direction described in references 3 and 5 (figs. 3(a) and 3(b)). The exact variation of downwash with Mach number between Mach numbers of 0.6 and 0.8 is not indicated, however, due to the lack of test points in this range.

When the Mach number is increased beyond that of force break, the downwash for a given normal force increases abruptly. This increase may be attributed primarily to the fact that, when the force-break Mach number of the wing is exceeded, the inboard sections of the wing experience a smaller reduction in normal-force coefficient than do the midsemispan sections of the wing, as shown in figure 21 of reference 1. These smaller reductions are due to the unexpected relieving effect that the slender, midwing fuselage has upon the flow over the wing, which is indicated by unpublished data. As a result, the normal-force coefficients of the inboard sections for a given over-all normal-force coefficient increase, and the downwash behind these sections increases. The increase may also be attributed to the fact that the downwash at

the survey positions is affected by the increase in the intensity and extent of the wake behind the wing associated with the onset of shock and separation of the flow over the upper surface of the wing. As in the case of the stalled wing, the flow behind the wing tends to move into the more intense wake and the downwash above the wake increases.

At the lower normal-force coefficients when the Mach number is increased beyond a value which is approximately 0.1 greater than that at which the downwash increases, the downwash for a given normal-force coefficient starts to decrease. This is probably caused by three changes which occur at approximately this Mach number: the differences between the normal-force coefficients of the midsemispan and inboard positions of the wing decrease abruptly, as shown in figure 21 of reference 1; the strength and extent of the intense wake produced by separation on the upper surface of the wing starts to decrease slightly, as indicated by unpublished data; and the extent of the field of flow in the stream direction decreases more rapidly because of the rapid increase in the extent of the region of supersonic velocities.

The nature of the changes of the downwash angle with Mach number for a given normal-force coefficient is, in general, the same as that of the changes that occurred behind the same wing without a fuselage present (reference 5), as shown in figures 3(a) and 3(b). The increase in downwash when the force-break Mach number is exceeded is much larger with a fuselage present than the increase is when no fuselage is present, however. This difference may be attributed primarily to the fact that, at these supercritical Mach numbers, the normal-force coefficients for the inboard sections with the fuselage present are much greater than they were when it was not present because of the relieving effect of the fuselage previously mentioned.

The apparent large differences between the downwash angles for a given normal-force coefficient at the two vertical stations and the presence of negative downwash for a zero normal-force coefficient for many conditions for all sweeps may be due in part to the presence of the fuselage, but are probably due primarily to errors in the settings of the yaw heads as mentioned in the section on errors and corrections.

Sweepback of 30°.- The variations of downwash angle with the normal-force coefficient at a given survey position behind the wing with 30° of sweepback are approximately the same at all Mach numbers up to those of force break for all normal-force coefficients up to that of stall (fig. 4(b)) where the downwash increases abruptly (figs. 2(c) and 2(d)). The data presented in figure 16 of reference 1 indicate that, with 30° of sweepback, the stall occurs initially at the tip, and the change in downwash may be attributed to the inboard shift of the load on the wing instead of to an inflow into a larger wake as it is for the wing without sweep. The rate of variation at a given survey position is somewhat greater than that for the wing without sweep at a given survey position; at a Mach number of 0.6 the rates of variation are approximately $4.1^{\circ}/C_N$

for the upper yaw head and $4.3^{\circ}/C_N$ for the lower yaw head for the wing with 30° of sweepback, compared with values of 3.5 and 3.6 for the wing without sweep. The differences between the values obtained at the two sweeps may be attributed not only to the differences of the fields of flow for the wing with sweep, but also to the variations of geometric parameters such as the relative survey positions and the lower aspect ratio.

When the Mach number is increased beyond that of force break, the rates of variation of downwash angles with normal-force coefficient increase. At a Mach number of 0.89 for the lower survey position it increases by as much as 75 percent.

The changes in the downwash angle with Mach number for a given normal-force coefficient behind the wing with 30° of sweepback are generally similar to those that occur behind the wing without sweep, but are delayed to somewhat higher Mach numbers (figs. 3(c) and 3(d)). When the Mach number is increased beyond that of force break, as indicated by the dashes in figures 3(c) and 3(d), the downwash for a given normal-force coefficient increases as it does behind the wing without sweep. The increase in downwash for the wing with sweepback is delayed by approximately the same Mach number increment as is the force-break Mach number for the same normal-force coefficient; the force breaks for the wing with sweep occur at Mach numbers approximately 0.07 greater than those at which the increases occur for the wing without sweep, and the increases in downwash for the swept wing occur at similar increments above those at which they occur for the unswept wing for the same normal-force coefficients. The increase in downwash is due to the same factors which produced the similar increase behind the wing without sweep: an inboard shift in the center of load due to the separation of the flow over the wing as shown in figure 22 of reference 1, and an expansion of the wake ahead of the yaw head.

The data for the higher normal-force coefficients indicate that the downwash started to decrease when the Mach number was increased beyond a value approximately 0.1 greater than that at which the increase in downwash occurred, as it did in the case of the wing without sweep. The change can probably be attributed to several of the same factors which produced the similar change in the downwash behind the wing without sweep, that is, the reduction of the amount of separation and rapid contraction of the field of flow.

The maximum increases in downwash at a given survey position behind the swept wing are somewhat greater than the maximum increase at the same yaw head behind the unswept wing for the same normal-force coefficient. This difference may probably be attributed to the more pronounced inboard shift in the center of load on the swept wing shown in figure 22 of reference 1 and to the fact that survey positions are lower

and farther forward in terms of the reference chord, which leads to a larger effect of a given increase in the relative extent of the wake in terms of the reference chord.

Sweepback of 45°.- The variations of downwash angle with normal-force coefficient for the wing with 45° of sweepback are very nearly the same for all Mach numbers up to the highest test value, 0.96, and for normal-force coefficients up to approximately 0.5 (figs. 2(e) and 2(f)). When the normal-force coefficient is increased beyond this value, the downwash angles increase rapidly. This increase is due to the onset of separation at the tip of the wing, which leads to an inboard shift in the center of lift, as shown in figure 16 of reference 1. At normal-force coefficients of less than 0.5, the downwash angle for a given normal-force coefficient decreases very gradually when the Mach number is increased up to the highest test value (figs. 3(e) and 3(f)). The rate of decrease is probably somewhat less than that for the unswept wing and the wing with 30° of sweepback due to the slower contraction of the field of flow for the wing with a larger amount of sweep.

The results presented in reference 1 indicate that there are no abrupt changes in the normal-force and profile-drag coefficients for a given angle of attack associated with an onset of shock and separation for the wing with 45° of sweepback up to the highest test Mach numbers for this configuration, and it would therefore be expected that there would be no abrupt changes in the downwash for a given normal-force coeffcient behind this wing with 45° of sweepback, such as there were behind the wing without sweep and 30° of sweepback, up to the highest test Mach numbers since such changes are associated with the onset of shock and separation on the surface of the wing.

Sweepforward of 30°.- The variation of downwash angle with normal-force coefficient at both survey positions behind the wing with 30° of sweepforward for a Mach number of 0.6 is very nearly linear up to a normal-force coefficient of approximately 0.5 (figs. 2(g) and 2(h)). Beyond this value of normal-force coefficient, the downwash angle increases as a result of inflow into the large wake which develops behind the wing-fuselage juncture, as shown in figure 17 of reference 1, because of separation at this juncture.

The variations of the downwash angles for given normal-force coefficients with Mach number for the wing with 30° of sweepforward are very erratic, varying considerably with normal-force coefficient and survey position (figs. 3(g) and 3(h)).

At the upper survey position and the lower normal-force coefficients, the downwash increases and then decreases abruptly. The changes occur at somewhat lower Mach numbers than do the similar changes behind the wing with 30° of sweepback. The relatively early increase in downwash may be attributed to an inflow into the wake ahead of and just inboard the yaw

head produced by separation at the wing-fuselage juncture. Unpublished data indicate that this separation occurs at relatively low Mach numbers in comparison with those at which separation occurs on the outer sections of the sweptforward wing or on the sweptback wing. The following relatively early decrease of downwash for the same condition can probably be attributed to the envelopment of the yaw head by the expanding wake. Unpublished data indicate that this envelopment occurs at approximately the same Mach number as that at which the decrease in downwash occurs.

At the lower survey position and the lower normal-force coefficients, the downwash does not increase and then decrease abruptly as it does at the upper survey position. It would be expected that the changes at this lower survey position would be similar to, but more severe than, those at the upper survey position, as is the case for the wings without sweep and with sweepback. The reason for the difference between the actual and expected changes is unknown.

At the higher normal-force coefficients, the downwash for a given normal-force coefficient decreases abruptly at a relatively low Mach number. This decrease may be attributed to the same factor which caused the similar but smaller decrease at lower normal-force coefficients, that is, to the envelopment of the yaw head by an expanding wake. The fact that the reduction in downwash is earlier and more abrupt at these higher normal-force coefficients can be attributed to a much earlier and more severe onset of separation at the wing-fuselage juncture for these conditions, which is indicated by unpublished data.

Because of these early, erratic changes in the downwash, an airplane with such a sweptforward wing and a tail at the survey positions may encounter large changes in trim. Since the erratic changes in the downwash angle behind the wing are due to the separation at the wing-fuselage juncture, it might be possible that they could be reduced by a considerable amount by reshaping the wing and fuselage near the juncture to reduce this separation.

Sweepforward of 45°.- The rates of variation of downwash angle with normal-force coefficient behind the wing with 45° of sweepforward increase gradually from values which are relatively large in comparison with those for the wing without sweep for low normal-force coefficients to extremely large values at the high normal-force coefficients at all test Mach numbers (figs. 3(i) and 3(j)). Because of this increase, the rate of variation of downwash with normal-force coefficient exceeds the rate of variation of angle of attack with normal-force coefficients (fig. 4). For example, this occurs at a normal-force coefficient of approximately 0.5 for a Mach number of 0.6 at the lower yaw-head position. These results indicate that a tail placed at a relative position corresponding to the survey positions behind a wing with this amount of sweepforward will contribute a destabilizing effect to an airplane at moderate normal-force coefficients. This increase in the rate of variation of downwash with

normal-force coefficient is due to a gradual increase in the strength and extent of the separated flow at the wing-fuselage juncture, as indicated by unpublished data. As mentioned previously, the air flows into the wake and the downwash above the wake increases.

This increase in the rate of variation of downwash angle with normal-force coefficient is greater at the lower survey position than at the upper position because the effect of wake is stronger at the lower position. The increase is generally more pronounced at the higher Mach numbers up to the highest test value, 0.96, than at the lower values due to an increase in the extent of separation with Mach number, indicated by unpublished data. For the lower survey position at the higher normal-force coefficients, the rate of variation decreases with Mach number because, as shown by unpublished data, at these conditions the wake starts to envelop the lower yaw head as it did behind the wing with 30° of sweep-forward at the higher Mach numbers.

The downwash for a given low normal-force coefficient generally decreases when the Mach number is increased up to the highest test value, as it does behind the other configurations (figs. 3(i) and 3(j)).

CONCLUDING REMARKS

The results of downwash-angle measurements, made at two vertical positions behind a high-aspect-ratio wing with an NACA 65-210 airfoil section and sweep angles of 0°, ±30°, and ±45°, in conjunction with a a fuselage at Mach numbers up to 0.96, indicate the following:

1. The downwash angle for a given normal-force coefficient behind the wing without sweep increases rapidly when the Mach number is increased beyond the force break and decreases sharply at a Mach number approximately 0.1 greater than that at which it increases.

2. The changes in the downwash angle for a given normal-force coefficient with Mach number behind the wing with 30° of sweepback are qualitatively similar to those that occur behind the wing without sweep, but they are delayed by sweep by approximately the same Mach number increment as is the force break.

3. The downwash angle for a given normal-force coefficient behind the wing with 45° of sweepback changes very slightly when the Mach number is increased up to the highest test value, as do the normal-force and profile-drag coefficients for a given angle of attack.

4. The variations of the downwash angles for given normal-force coefficients with Mach number for the wing with 30° of sweepforward are very erratic, varying considerably with normal-force coefficient and survey position.

5. The rates of variation of downwash angle with normal-force coefficient for the wing with 45° of sweepforward are very large at moderate normal-force coefficients.

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TABLE I

GENERAL DIMENSIONS

Symbol	Description	Dimensions				
Δ_r	Sweep of 25-percent chord line of original wing, deg.	0	30	45	-30	-45
b	Span, in.	37.8	34.2	28.2	33.8	27.4
c_r	Root chord, in.	6.0	6.64	7.97	7.23	9.03
c_g	Tip chord, in.	2.40	2.53	3.07	2.66	3.33
c_f	Chord at intersection of wing and fuselage, in.	5.64	6.20	7.27	6.73	8.20
S_a	Area of wing assuming wing straight through fuselage, sq in.	158.6	156.2	154.4	166.4	167.8
A_a	Aspect ratio assuming wing straight through fuselage	9.0	7.5	5.2	6.9	4.5
	Taper ratio of wing outboard fuselage	2.35	2.45	2.37	2.53	2.46
l	Distance from quarter chord of mean aerodynamic chord of wing assuming wing straight through fuselage to points of measurement	18.00	14.70	14.0	21.44	22.88
h	Distance from wing chord line extended to points of measurement	4.20 3.0	4.20 3.0	4.20 3.0	4.20 3.0	4.20 3.0
s	Distance from surface of plate to points of measurement	4.7	4.7	4.7	4.7	4.7
l/c_f		3.19	2.37	1.92	3.19	2.79
h/c_f		0.745 0.532	0.677 0.484	0.578 0.413	0.624 0.446	0.512 0.366
$2l/b$		0.95	0.86	0.99	1.27	1.67
$2h/b$		0.222 0.159	0.246 0.175	0.298 0.213	0.249 0.178	0.307 0.219
s/b		0.25	0.27	0.33	0.28	0.34

[redacted]

TABLE II

TEST POINTS

$\Lambda_r = 0^\circ$

M	α, degrees
0.600	-2, 0, 2, 4, 7, 10
.750	-2, 0, 2, 4, 7, 10
.800	-2, 0, 2, 4, 7, 10
.850	0, 2, 4, 7
.890	0, 2, 4, 7
.925	0, 2, 4, 7

$\Lambda_r = 30^\circ$

M	α, degrees
0.600	-2, 0, 2, 4, 7, 10
.800	-2, 0, 2, 4, 7, 10
.580	-2, 0, 2, 4, 7
.890	0, 2, 4, 7
.925	0, 2, 4, 7
.960	0, 2, 4, 7

$\Lambda_r = 45^\circ$

M	α, degrees
0.600	-2, 2, 7, 10, 13
.800	-2, 2, 7, 10
.890	-2, 2, 7, 10
.925	-2, 2, 7, 10
.960	-2, 2, 7, 10

$\Lambda_r = -30^\circ$

M	α, degrees
0.600	-2, 0, 2, 4, 7, 10
.800	-2, 0, 2, 4, 7, 10
.850	-2, 0, 2, 4, 7
.890	0, 2, 4, 7
.925	0, 2, 4, 7
.960	0, 2, 4, 7

$\Lambda_r = -45^\circ$

M	α, degrees
0.600	-2, 2, 7, 10, 13
.800	-2, 2, 7, 10
.890	-2, 2, 7, 10
.925	-2, 2, 7, 10
.960	-2, 2, 7, 10

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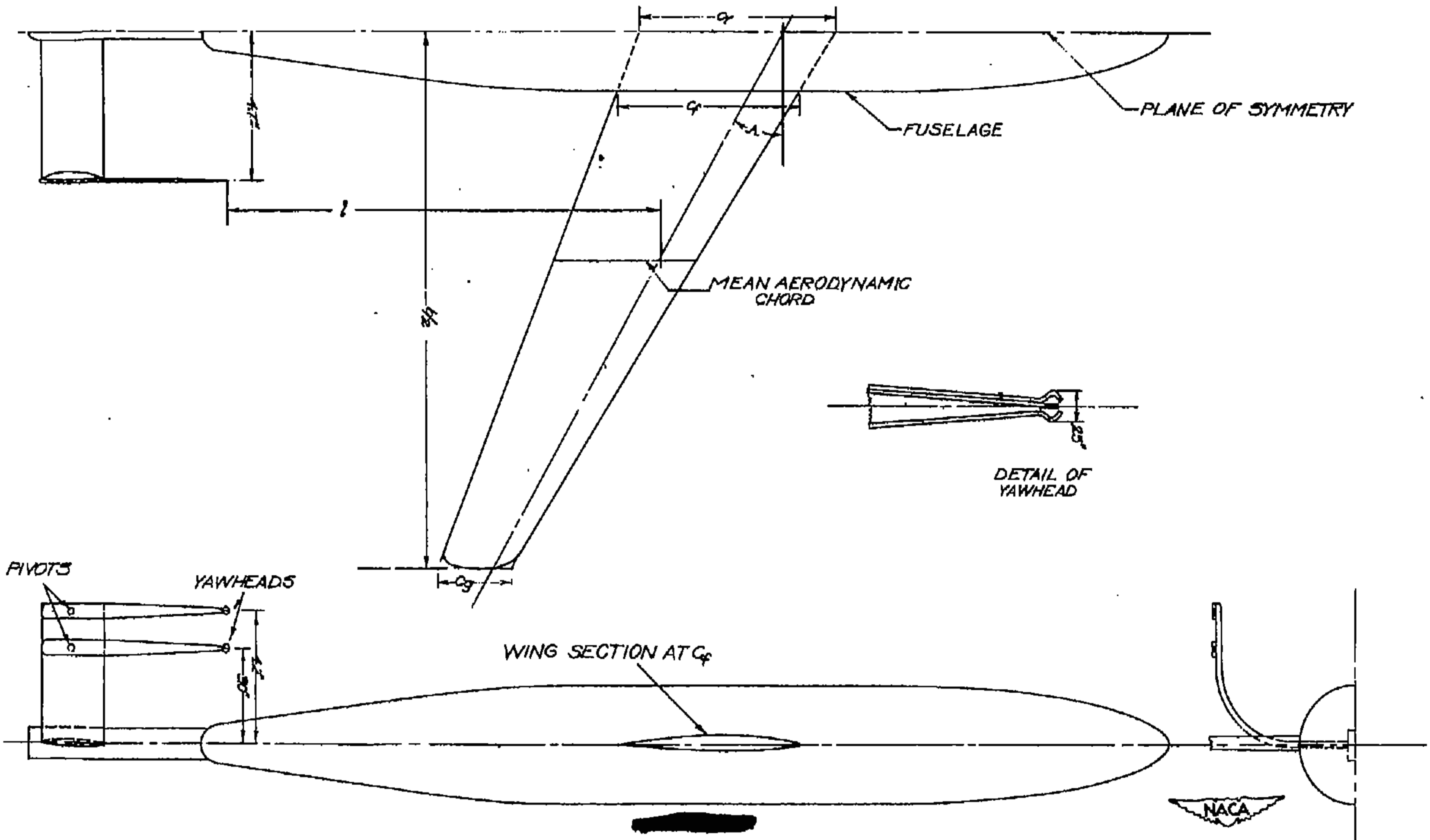

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FIGURE 1.- GENERAL DIMENSIONS OF APPARATUS.

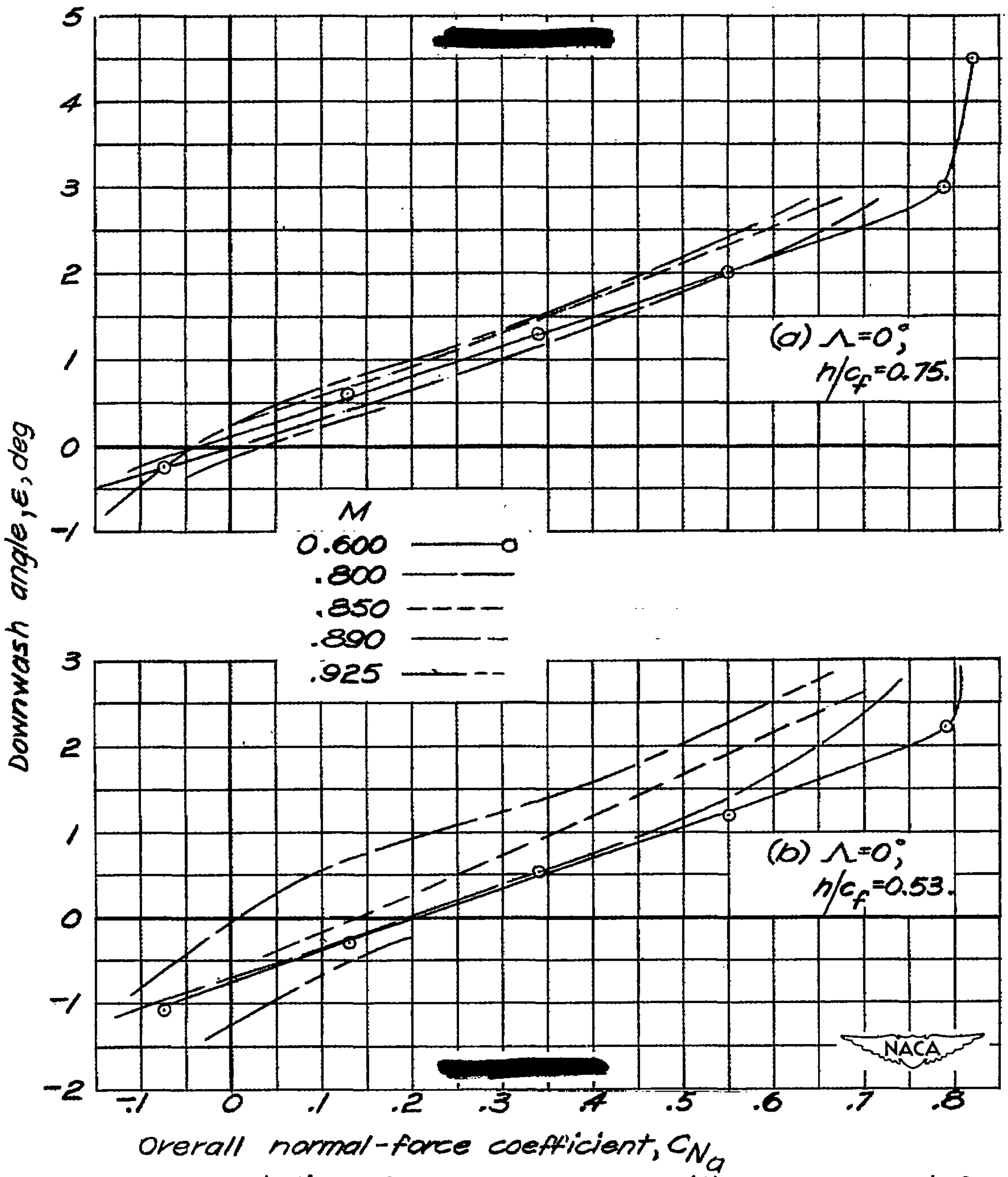
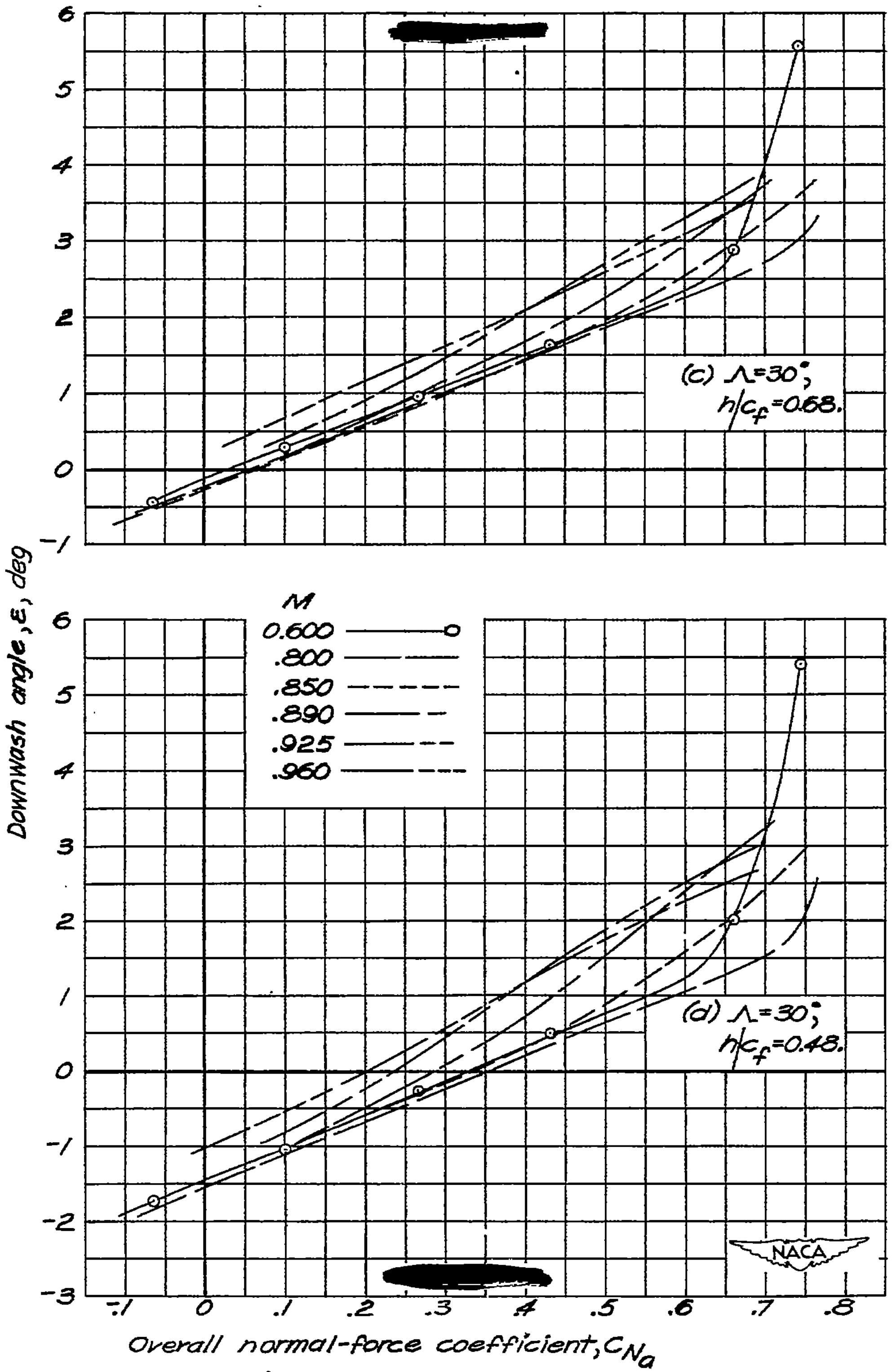


Figure 2.- Variation of downwash angle with overall normal-force coefficient for various sweep angles and Mach numbers.



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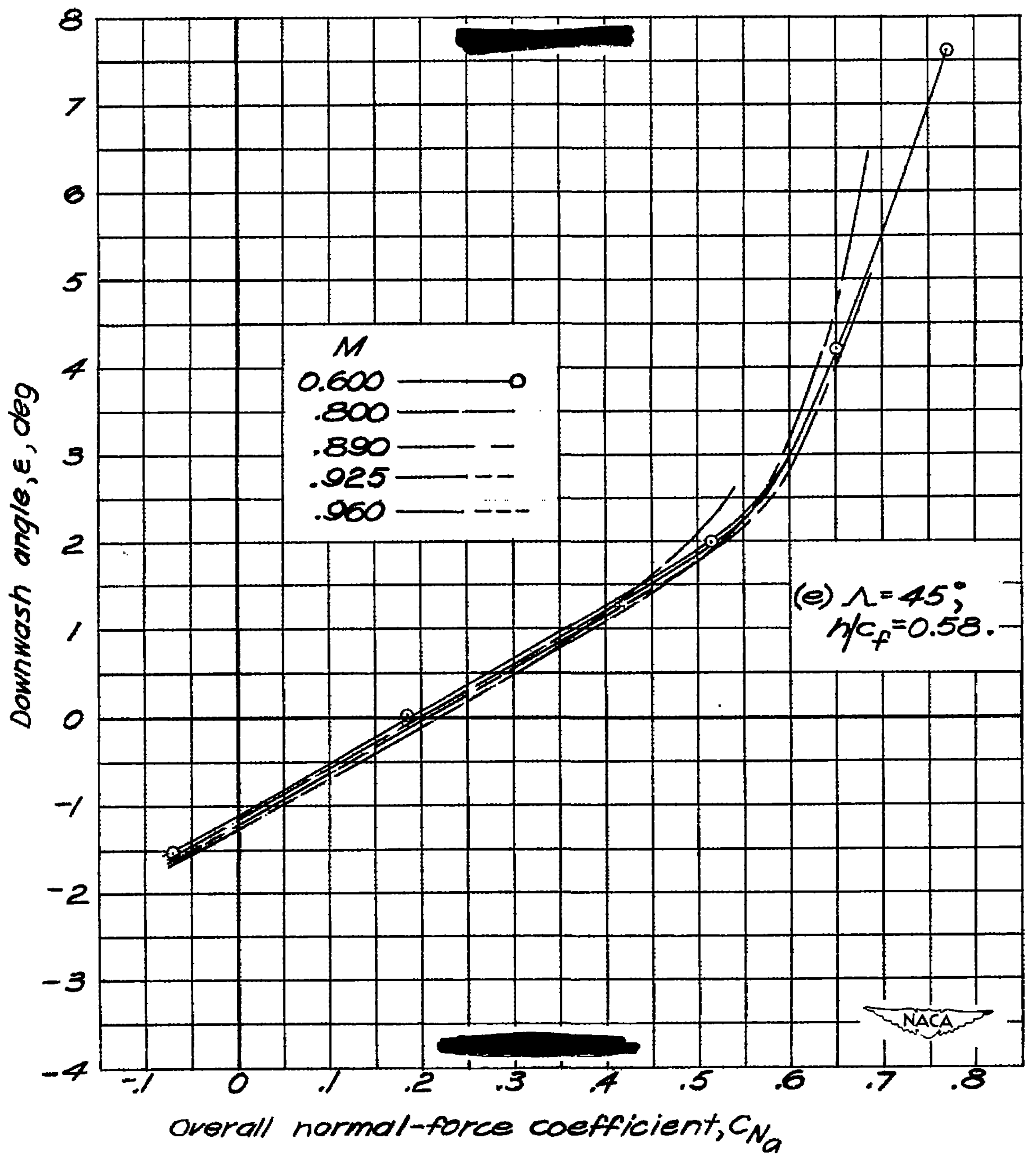

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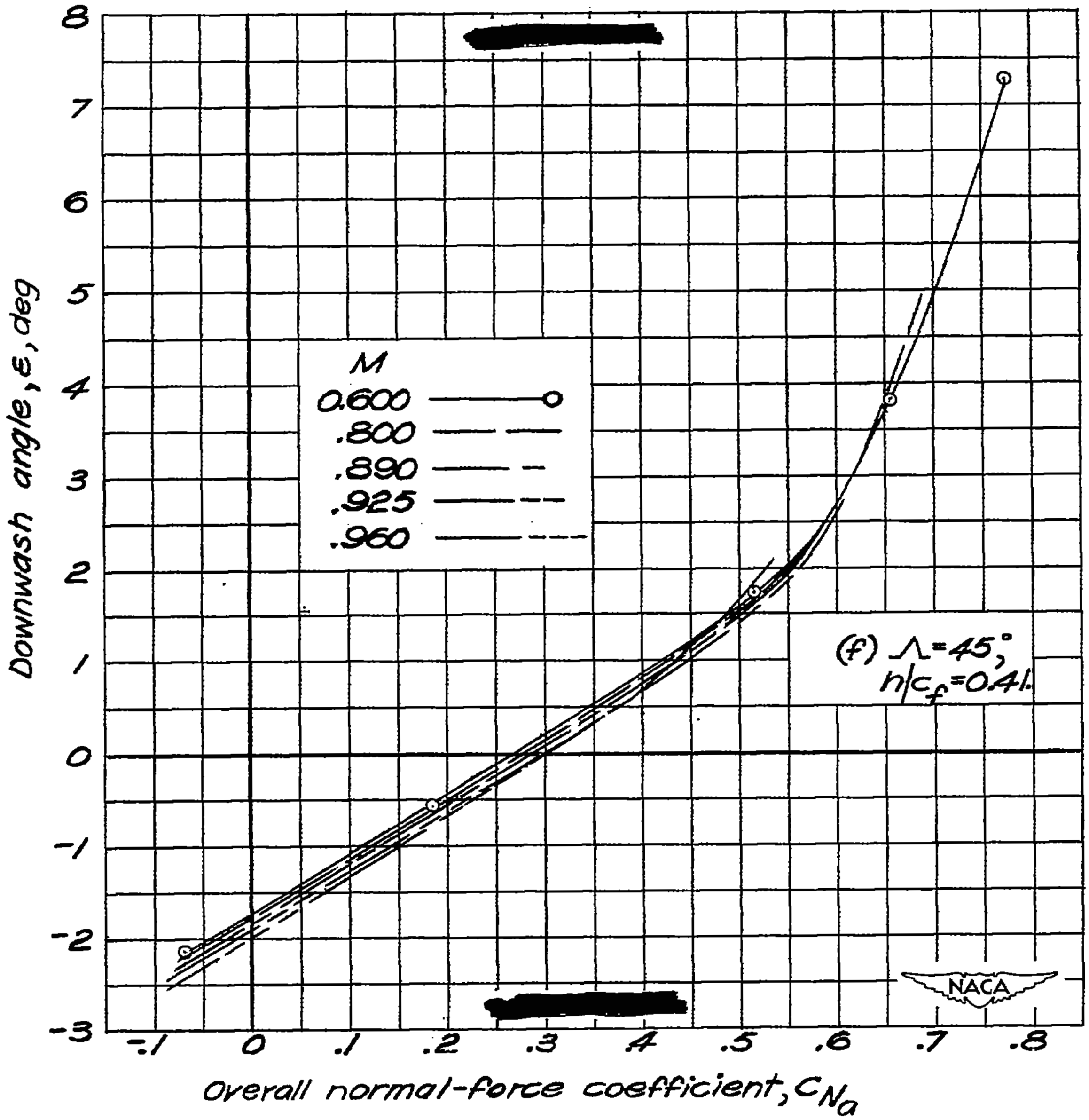

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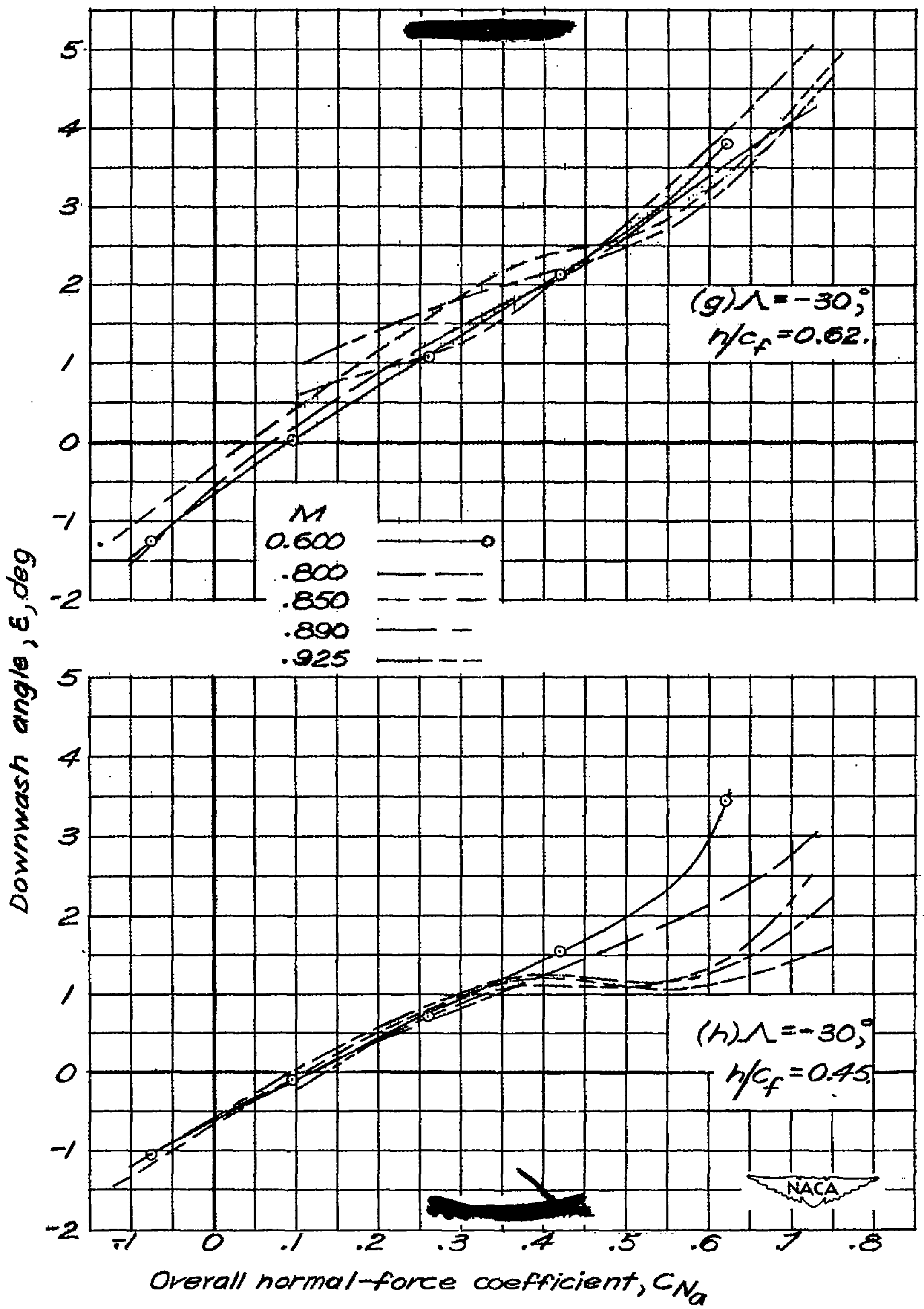

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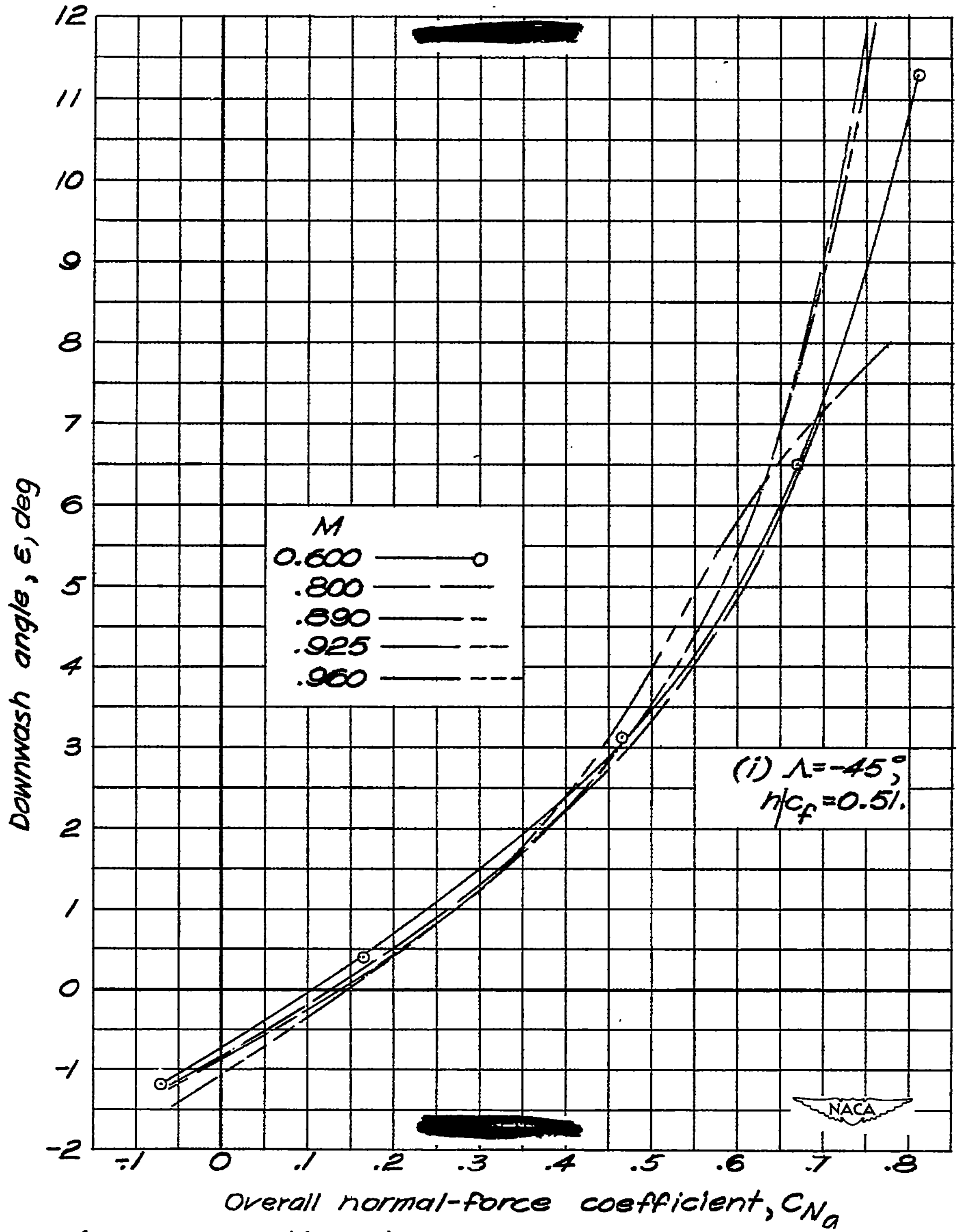

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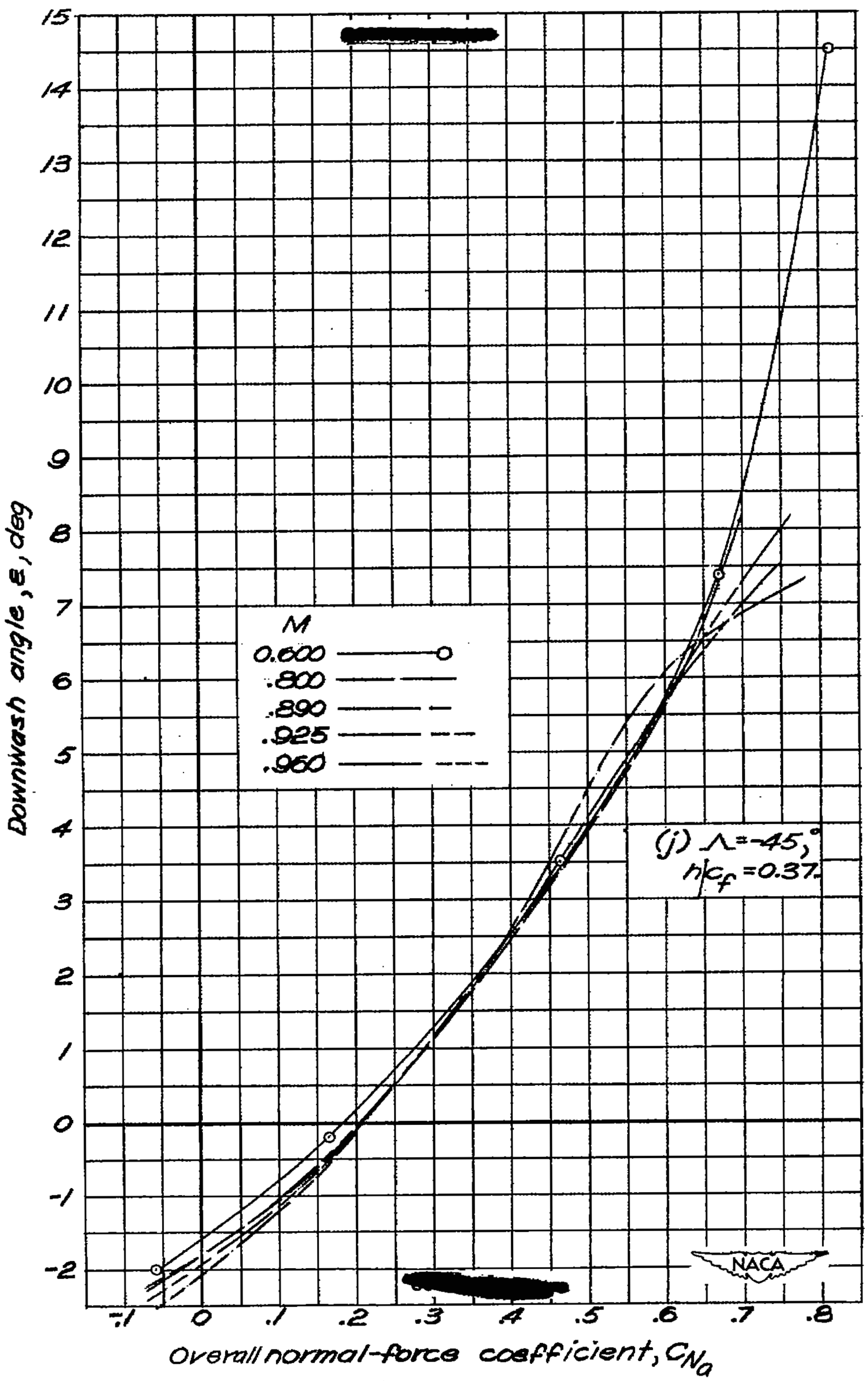

Figure 2.—Concluded.

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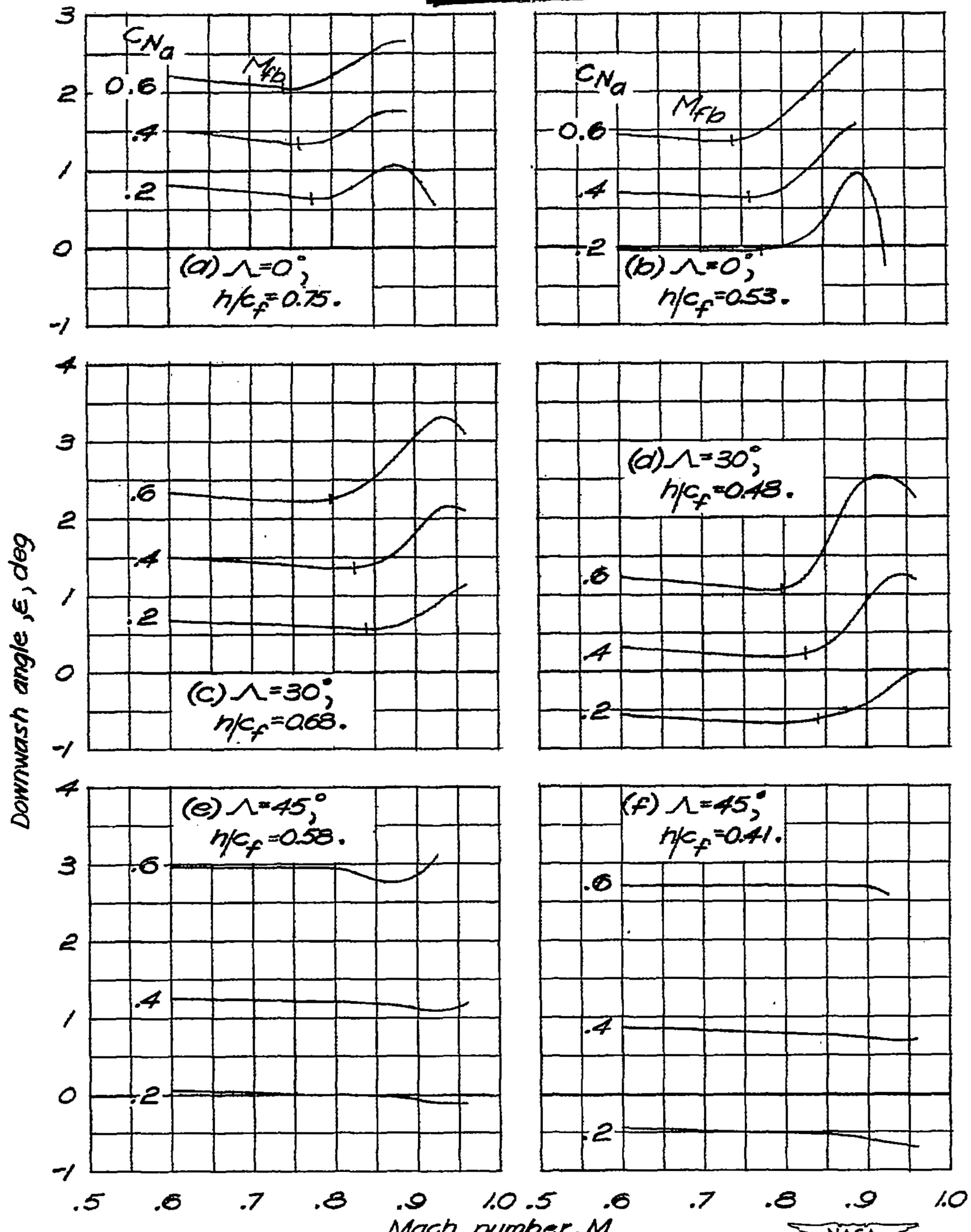

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Figure 3.– Variation of downwash angle with Mach number for various sweep angles and overall normal-force coefficients.

[redacted]

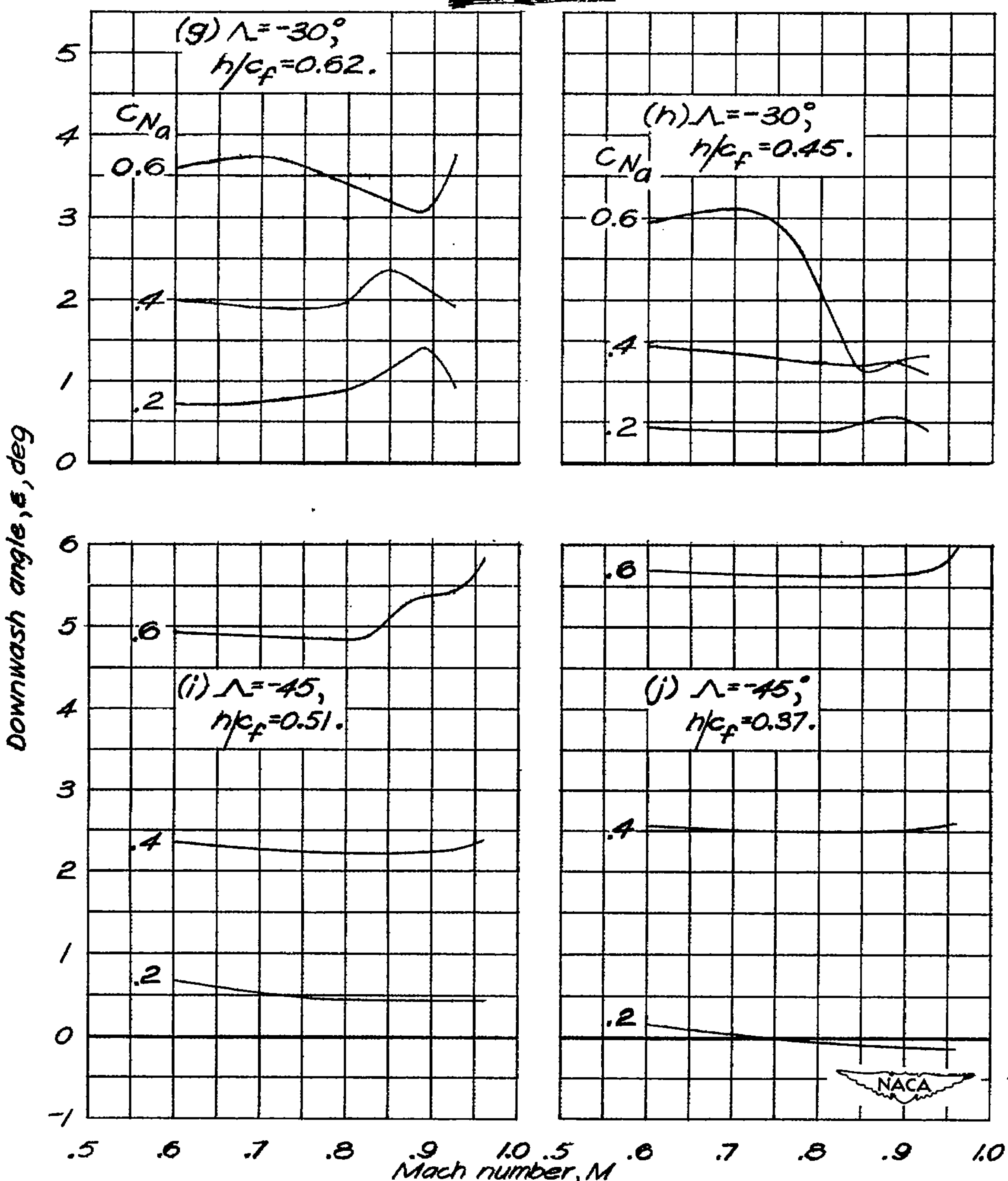

Figure 3.—Concluded.

[redacted]

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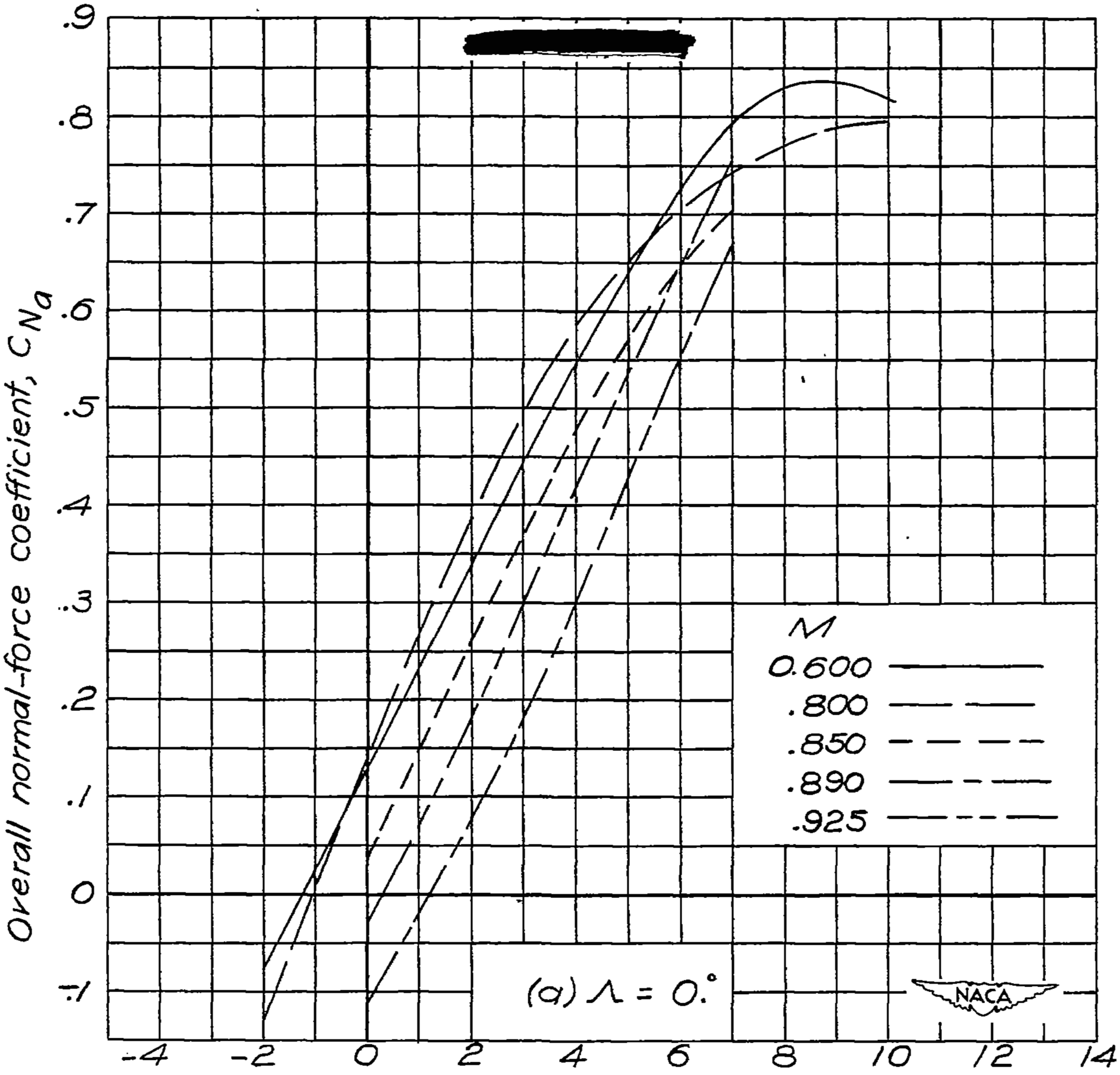

Figure 4.— Variation of overall normal-force coefficient with angle of attack.

[redacted]

[redacted]

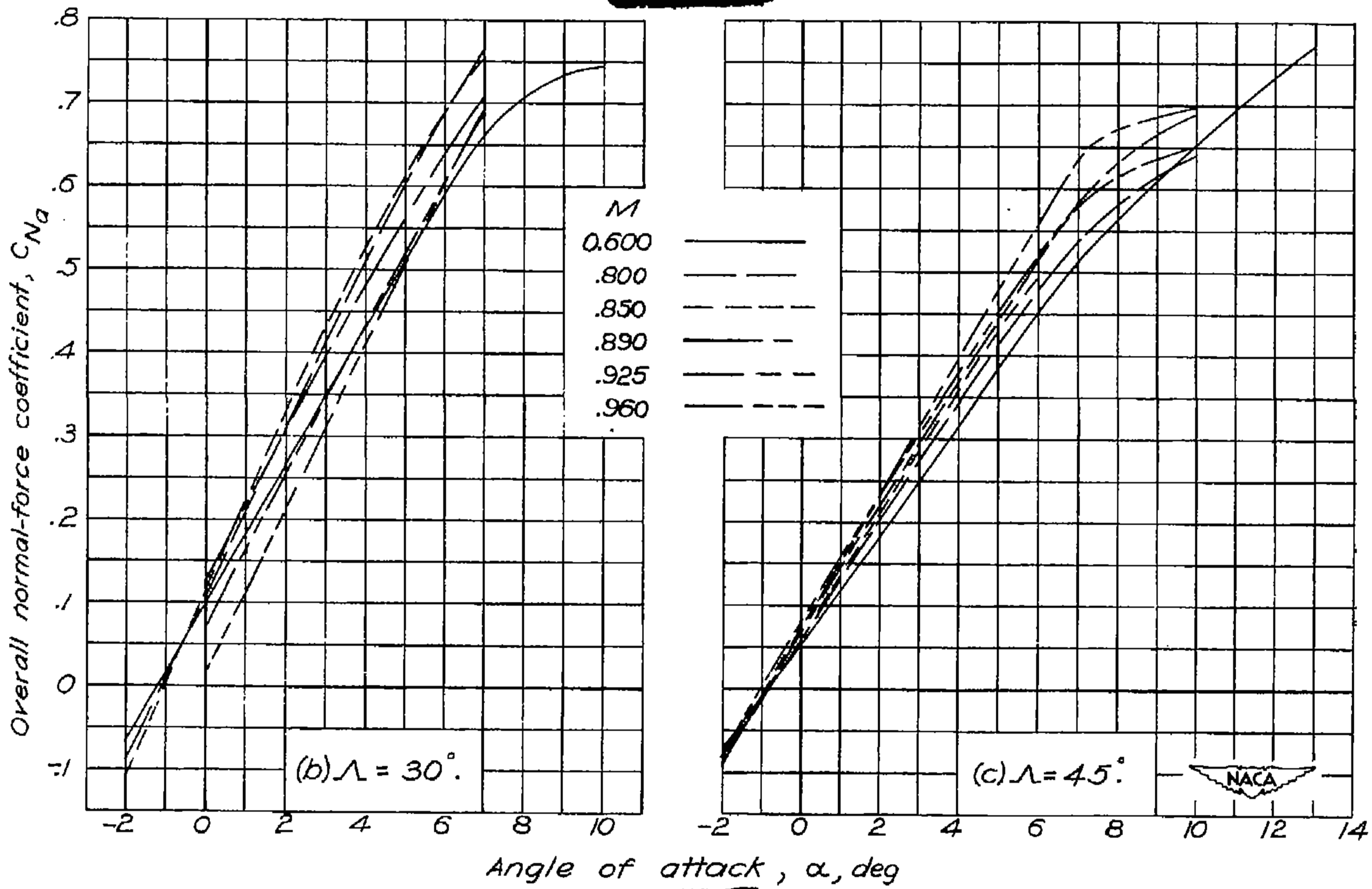

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Figure 4.- Continued.

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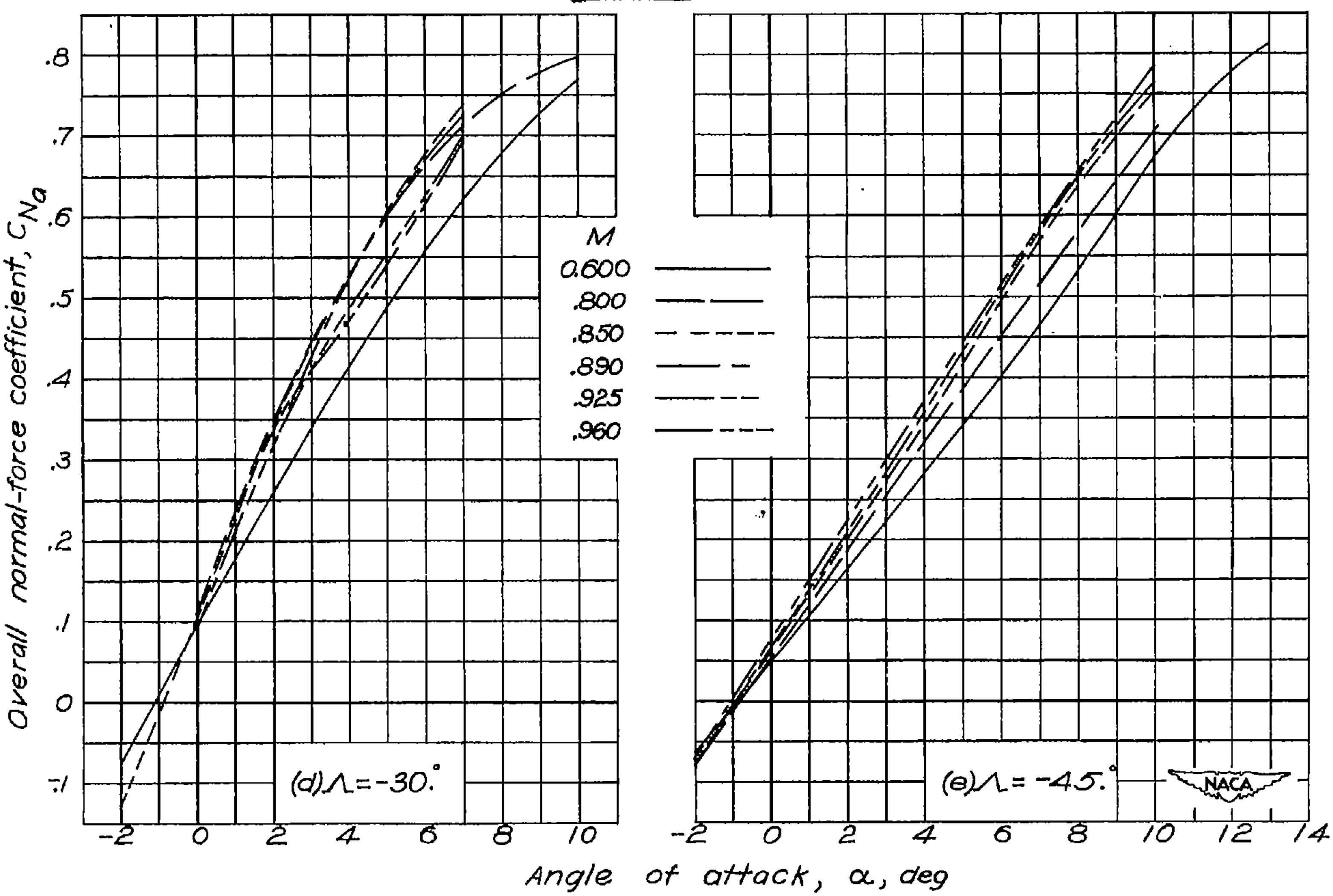

Figure 4.- Concluded.

[redacted]